Conductron Corporation

SIX MONTHS SUMMARY REPORT ON ECHO II DATA REDUCTION AND ANALYSIS

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ABSTRACT

This report describes the analysis and results based upon the analog records of radar observations during the post launch period of the ECHO II flight test. The statistical properties of the radar cross section return are examined to determine the mean values of the cross section and the nature of the scintillations of the cross sections. Anomalies in the data are examined and explanations of these anomalies in terms of holes, plasmas, gross distortions, etc., are examined and discarded. It is concluded that the flight test balloon achieved its 135 foot diameter spherical shape with generally minor surface variations and that the balloon can be used effectively for communications purposes.

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I. INTRODUCTION AND SUMMARY

1.1 Background Information

1.1.1 Historical Background

This report describes the collection, reduction, and analysis of data received from radar observations of ECHO II. It summarizes work done during the first five months of the third phase of the continuing ECHO II satellite analysis program sponsored by NASA/GSFC. We shall now briefly discuss the first two phases so that the work reported on here can be viewed in the context of this continuing effort. In the first phase of the program 12-foot circular segments of ECHO II material were maintained on a support structure and the radar cross-section was measured on a radar range. Monostatic and bistatic (up to angles of 30°) radar cross-section measurements were performed at L and C band frequencies, for varying conditions of tangential skin stress, and after relaxation of pressure. At the conclusion of this first phase this segment measurement technique had been developed to the point that it could reliably predict the mean cross-section of the balloon as a function of the balloon inflation history. Concurrently, techniques were developed to determine the satellite shape and surface characteristics as revealed by radar signature characteristics of the return from the balloon. These radar signature characteristics, studied as functions of look angle, and frequency, included mean radar cross-section, scintillation of the radar return, and the auto-correlation function of the time varying cross-section history.

The second phase of the program continued the work started in the first phase and in addition included reflectivity measurements of the balloon during static inflation tests at Lakehurst Naval Air Station. These measurements were performed at L-band and C-band frequencies, for small increments of pressure, ranging from 400 PSI to 12,000 PSI tangential skin stress, and over a continuous bistatic aspect range from 0 - 30°. The report issued after this portion of the program was completed (Reference 1) discussed the reflectivity of the balloon as a function of surface stressing, frequency, polarization, and viewing aspect and contained radar cross-section patterns taken at three separate surface stresses -

2,800, 4,800, and 7,400 PSI. Photogrammetric maps showing the variation of the surface from spherical were prepared. High correlation was found between reflectivity computed from these maps and the measured values.

1.1.2 Objectives of the Flight Test Data Reduction and Analysis Program

The data reduction and analysis program is intended (1) to provide information on the degree of rigidity attained, the balloon surface characteristics and geometry, and the orientation of the satellite; (2) to determine the dynamic radar characteristics of ECHO II; and (3) to test the usefullness of static radar data in predicting the communication properties of passive inflatable satellites.

The satellite was launched by NASA/GSFC on the morning of Saturday, 25 January 1964. Various radars were assigned by the DOD and other organizations to furnish NASA/GSFC with data for analysis from which can be determined the following specifics:

a. characteristics of the balloon surface and geometry,
b. comparison of radar returns as obtained from Phase I and II ground measurements with radar data for the orbiting balloon,
c. balloon spin axis orientation and spin rate.

The radar data was taken at frequencies from UHF through X-band and telemetry data was collected from beacons operating at frequencies of 136.170 MC and 136.020 MC.

1.1.3 Data Collection

Under the program observers were stationed at the following sites:

a. The L-band radar at Millstone Hill, Massachusetts,
b. Wallops Island, Virginia, where S, X, and UHF radars were used, and
c. The S-band RAMPART radar at White Sands Missile Range.

Data from the sites listed were furnished in the form of analog pen records. In addition, analog records were received from the C-band radars at Kwajalein, and Ascension Island; and beacon analog records and radar data taken at the Royal Radar Establishment (RRE) at Malvern, England, were made available. All of these analog records formed the basis for several reports (References 2 and 3) on the interpretation of the collected radar data and are the main data used for this Summary Report. A series of data processing and statistical programs are now prepared for the IBM 7090 computers (at Goddard Space Flight Center) to permit intensive analysis of the radar data stored on magnetic tape.

The data collection effort was very intensive during the first two weeks ECHO II was in orbit so as to examine balloon behavior during initial pressurization and during the first continuous sunlit period of eleven days and the initial eclipse period. Thereafter most radar establishments collected ECHO II data on a non-interference basis with other measurements until observations were again increased during the onset of the second sunlit period. The analog data records are very difficult to use for extensive analysis of balloon properties; therefore, the recordings on magnetic tape must be considered to provide the primary data source for balloon analysis. Nevertheless, it has proven possible to determine a good deal of information from the analog recordings with considerable confidence in the results. We summarize below the presently available information.

1.2 Summary of Results

1.2.1 Mean Radar Cross Section

The radar cross section of a perfectly conducting sphere whose radius is much larger than the wavelength can be calculated by the simple formula $\sigma = \pi R^2$. For all radar wavelengths of interest in this program the radius of the ECHO II balloon satisfies this criterion. Thus the expected cross section of ECHO II would be about 1320 square meters or 31.2 db above a square meter. We shall refer to this value as the nominal radar cross section of ECHO II.

On the basis of the analog data available this expected nominal radar cross section has been achieved.

Of those balloon parameters which can be determined by an examination of the analog strip chart pen recordings the mean radar cross-section is probably the only one which can be obtained with high reliability. Systematic variations in mean radar cross-section may exist which are apparent only when the magnetic tape data is processed. During the contract period Conductron has prepared two computer programs which provide NASA the capability to easily extract mean radar cross-section histories from the data tapes which can then be examined in a systematic way. Both short and long time history variations of the radar cross-section can be examined by these programs and this will be done for those passes on which data is available.

1.2.2 Scintillation

The return, at C-band, fluctuates with a $\pm$ 6 db variation with a variable period. Data processing has shown that at L-band the standard deviation of the variation is approximately 20 percent less than at C-band.

1.2.3 Polarization and Frequency Effects

Theoretical analysis and experimental results given in Reference 1 have shown that no significant polarization dependency is to be expected for ECHO II. This has been verified by the flight test data, with one possible exception. Some of the UHF data indicates phase dependence on polarization, but not amplitude dependence. This is an apparent contradiction, and has not been resolved.

Apparent polarization effects present in the Wallops Island UHF data have been shown to be quantitatively consistent with Faraday rotation effects.

Balloon scintillation was determined from radar recordings taken at several different frequencies at different radar sites and for separated time intervals. The dependence of the return on frequency or, equivalently, wavelength at a given moment of time and for the same aspect angles to the balloon is an interesting question which it is not possible to answer definitively using only analog recordings. By simultaneously looking at the balloon at different frequencies from the same ground site, it should be possible to determine surface deformations which result in frequency dependent changes in the radar cross-section recordings. The dependence on frequency will be analyzed by a comparison of data tapes for which there are simultaneous observations of the balloon at several radar frequencies such as UHF, S-band and X-band. If the balloon were a perfectly conducting sphere with no irregularities or deformations the radar return would not be expected to show any dependency on frequency. However, the postulated "wedge effect" discussed in Section 1.2.6 would be expected to show a dependence on frequency which will be discernable in the computer processed data.

1.2.4 Spin Rate

The apparent presence of an approximately one-hundred second period in the analog data substantiated by the beacon data leaves little room for doubt that the balloon is rotating with this approximate period. A computer program prepared for NASA/GSFC which computes power spectra should permit inspection of a possible long term spin rate change.

1.2.5 Anomalies

The following was noted from a visual inspection of analog records:

a. A pronounced drop in average return of approximately 10 db was noted on some of the analog pen records. This effect appears intermittently with the drops in return enduring for as much as several seconds. When this effect is present it appears with a period which is a multiple of approximately 50 seconds.

b. The 50 seconds of return following this drop out appear to have a significantly different fine structure from the 50 seconds preceeding.

c. The return in general has a spikey appearance dipping about 25 db for very brief periods.

A number of hypotheses may be advanced to explain these peculiarities in the radar signature. Those which seem more probable are in the process of investigation. The best explanation is that the balloon is in general spherical but has deformed areas.

Four alternative hypotheses have been examined in some detail and three have been tentatively rejected. These are:

a. The presence of an ionized cloud about the balloon due to escaping gas.

b. Multipath effects, i.e., cancellation and reinforcement of the returned signal by reflected signals from the earth.

c. The existence of a hole in the surface of the balloon.

Item c above deserves special comment here in that a "hole in the balloon" was explicitly reported by RRE, Malvern, England, and a U.S. tracking station shortly after ECHO II was launched. The theoretical reasons which lead Conductron to reject this possibility are discussed in detail in Section III of this report.

Conductron believes a fourth hypothesis, which is a more plausible explanation of the drop in radar cross section, is that the balloon rotation causes the portions of the balloon containing the solar panels and telemetering beacons to bulge out into a wedge shape. The cross section of such a shape has been computed and could account for the effect as noted in the Millstone Hill data* (Figure 1). This hypothesis is subject to further test by comparing data taken at other frequencies in the continuing data reduction program.

The computer programs now on hand and in the process of development will make possible more definitive statements both about the existence of any anomalies and their possible nature. For example, a new technique for analyzing the effect on radar cross section returns of more than one scatterer has been developed and may be used to test this conjecture.

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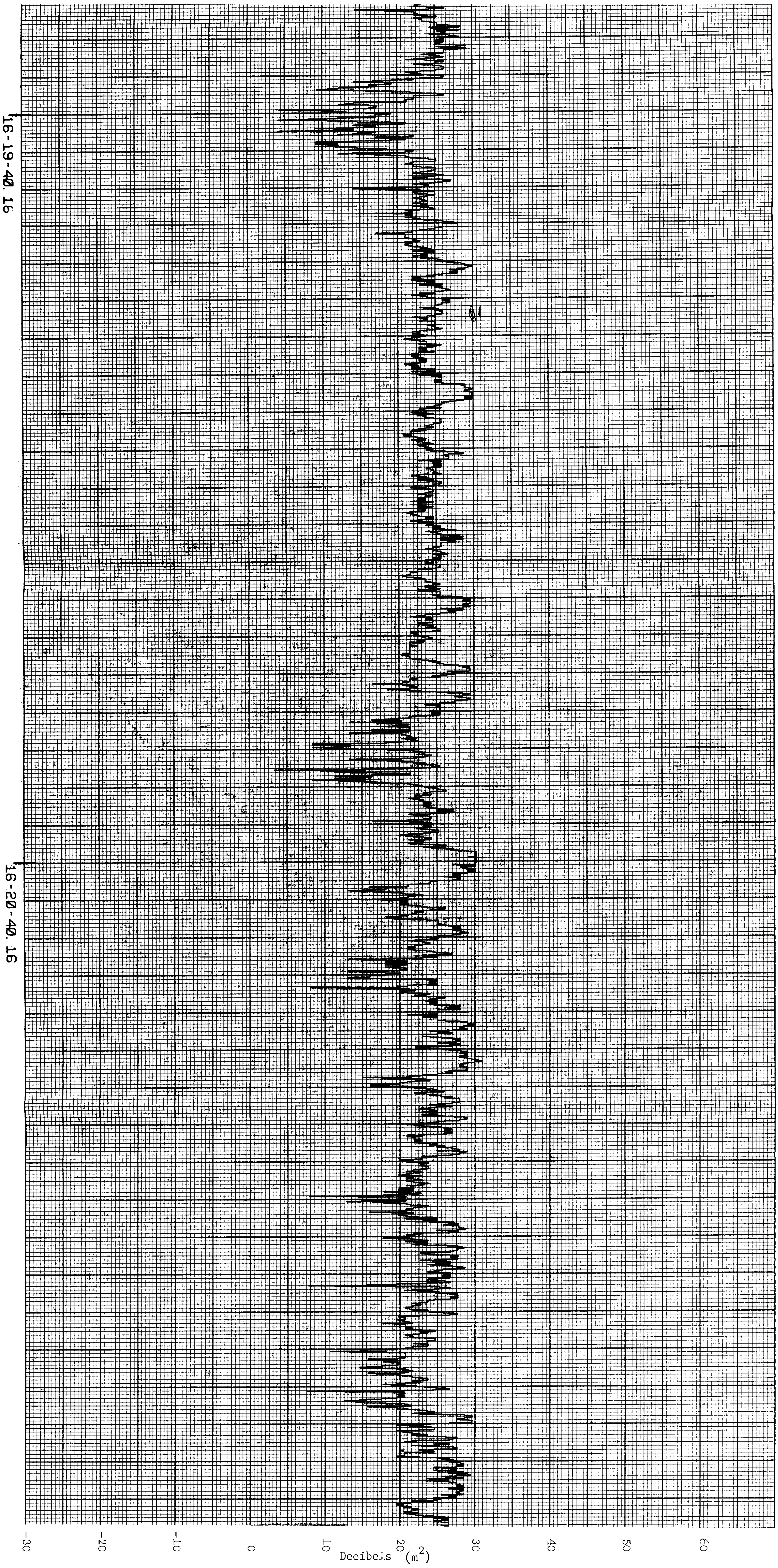
* It should be observed in examining Figure 1 that the apparent mean radar cross section of 23-24 db is subject to calibration uncertainties of perhaps as much as 6 db.



TYPICAL ECHO II RADAR CROSS SECTION DATA, 28 January 1964, Millstone Hill Radar Site

FIGURE 1

This technique is described in Reference 4.

The presence of any periodic effects will be fully verified by digital data processing and their significance will be determined. Any hypotheses about the physical shape of the balloon can then be accepted, modified, or rejected on the basis of the results.

The data processing program will provide the capability for large-scale, precise analysis of the statistics of the radar return for future radar observed satellites.

1.2.6 Plasma Effects

Since the sublimating material used to inflate the ECHO balloon to its proper shape is vented to the exterior through a system of small holes in the periphery of the balloon, the ionization of this material by the solar radiation flux could conceivably form plasma densities of sufficient magnitude to cause radar perturbations at the frequencies of interest. Based on information supplied by NASA/GSFC this possibility has been studied and rejected as being improbable for the reasons given below.

For a 200-micron internal balloon pressure NASA/GSFC estimates the electron density along a sphere of one cm around the hole would be 10^{10} electrons/cm^3, and this would decrease to 10^7 electrons/cm^3 as the radius of the hole becomes equal to the balloon radius. The build-up of ionization around the balloon is precluded by the fact that any free charge formed near the satellite must cut lines of force of the earth's magnetic field. At the high orbital velocities encountered, the gyration radius of a free electron in the magnetic field is small so that instead of being carried along in orbit, free charge will diffuse along the magnetic field lines. Consequently, ionization will be swept away from the balloon as it is formed by the combined forces of the magnetic field and the ambipolar diffusion of the ionized gas.

Since the beacon frequencies at 136 MC are at the lower end of the frequency range of interest, any plasma effects which occur would potentially have their greatest capability for distortion on the observed beacon pattern. However, due to the relative location of the vent holes and the beacon antennas, calculations indicate that plasma effects will be negligible.

Similarly, for radar frequencies of approximately 1300 MC or higher, it is found that the index of refraction of the plasma differs from unity only over a region which is small compared to the wavelength of the incident radiation. The ionized regions consequently act as Rayleigh scatterers with a small radar return.

1.2.7 "Echo Box" Effect

It has been reported by RRE at Malvern that the S-band radar data obtained exhibits the following anomaly: Subsequent to the reflection of the main pulse, which is of 10μs duration, there is observed an exponentially decaying train of pulses. The explanation that has been supplied with the data for this phenomenon is that an oblong hole (1.5 meters x 0.5 meters) in the balloon has been excited by the incident field, which in turn has excited a mode in the balloon, which in turn is reflected, re-excites the hole, etc., analogous to the familiar "Echo box".

On the basis of the reported data the explanation that has been offered does not appear to Conductron to be correct. The pulse train spacing is reported to be of the order of 10μs. Taking into account the pulse width, the balloon would then be acting as a 20μs delay line. The two way path of any mode excited in the balloon is 270 feet, corresponding to a free space time of 0.27μs. The mode velocity is therefore $.27/20 \approx 1/80$ of free space velocity. Geometric optical approximation shows that the principal mode has a velocity of $\frac{1}{\sqrt{2}}$ of free space velocity.

Therefore the "Echo box" effect would have to be related to a very high order mode, i.e., to a very large number of internal reflections. Furthermore, it would depend upon not only this high order mode being excited, but no lower order modes being excited. This is so unlikely it can be considered impossible.

Somewhat similar trailing effects have been reported by other observers but these have been attributed by the observers to multi-path phenomena associated with low elevation angles or no explanation has been proffered.

II. COMMUNICATIONS

2.1 Quantitative Results

Quantitative questions have been examined in connection with the effect of variations in the ECHO II radar cross sections on the functional use of the balloon as a passive communications satellite. The findings depend upon present understanding of the statistical properties of the radar cross section, and are to be regarded as tentative, to be confirmed, or modified as the data processing continues.

On the basis of computations performed below, using typical system parameters, it is concluded that:

a. Fading rates (in carrier power) are unacceptable for high quality communication at UHF, marginally acceptable at 2000 MC and acceptable at 5000 MC. In practical terms this means that the ECHO II is suitable for frequency modulated transmission at carrier frequencies greater than 2000 MC.

b. Radar cross section scintillation of the ECHO II introduces noise into the information channel for amplitude modulated signals. For amplitude modulated voice transmission this noise can be expected to significantly degrade quality, whereas for telegraphic or slow data rate communication, the noise can be expected to be negligible.

c. Although the radar data is monostatic (receiver and transmitter at same location) it can be used to predict bistatic communication performance (receiver and transmitter separated).

For a high quality speech transmission, with a 20 KC bandwidth, the following system parameters have been postulated:

Noise temperature - 1000° K

Signal/Noise Figure - 25 db

Antenna diameter (receiver and transmitter) - 60 ft

Transmitting power - 1 KW

Modulation - F.M.

If σ_m is the minimum balloon cross section required to obtain the 25 db signal/noise figure,

$$\sigma_m \sim 10^3 \lambda^2,$$

where λ is the wavelength of the carrier. For a 40 foot antenna this number would be multiplied by 9/4. This gives the table:

Carrier Frequency	$\frac{\sigma_{min}}{\sigma_o}$ (60 ft antenna)	$\frac{\sigma_{min}}{\sigma_o}$ (40 ft antenna)
300 MC	- 1.2 db	+ 2.3 db
2000 MC	- 17.7 db	- 14.2 db
5000 MC	- 25.6 db	- 22.1 db

Minimal $\frac{\sigma_{min}}{\sigma_o}$ to achieve 25 db signal/noise ratio (σ_o = 1320 m^2) at 1 KW transmission.

From this table, the fading rate (percentage of time the balloon cross section is less than σ_{min}) can be computed, assuming that A = 6. (A is defined in 2.2 below):

Carrier Frequency	Fading rate (60 ft antenna)	Fading rate (40 ft antenna)
300 MC	76 percent	90 percent
2000 MC	3 percent	8 percent
5000 MC	.05 percent	.5 percent

The value A = 6 used in these computations is conservative. From data observed, A, in general will be smaller, giving lower fading rates.

2.2 Radar Cross Section Statistics

The data obtained for a run of length T provides a record of the cross section, $\sigma(t)$, as a function of time. The mean cross section σ_o, is defined as:

$$\sigma_o = \frac{1}{T} \int_0^T \sigma(t)\, dt$$

Let $f = \sigma(t)/\sigma_o$. Regarding f as a random variable, the mean value of f, $\langle f \rangle$, is clearly unity, and the variance of f, $V_f = \langle f^2 \rangle - 1$.

If the cross section is recorded on a db scale, the recorded quantity is

$$10 \log f.$$

It is assumed that the random variable, 10 log f, is normally distributed with mean m and variance A^2. This assumption is consistent with the observed data.

It is then a simple matter to obtain the following relationships:

$$m = -10 \log \sqrt{\langle f^2 \rangle} = -\frac{\ell n\ 10}{20} A^2 \sim -.115\ A^2.$$

These relationships enable one to find any two of the quantities, m, A, V_f, from the third.

On the basis of data received, both in the flight test and in the static inflation tests, typical values of A are 3 at the lower frequencies and 6 at the higher frequencies, giving corresponding values for m of -1 db and -3 db.

The cumulative probability distribution for f is

$$\begin{array}{ll} \Phi\left(\frac{10 \log x - m}{A}\right) & x > 0 \\ 0 & x \leq 0 \end{array} ,$$

where

$$\Phi(u) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} e^{-\frac{t^2}{2}}\ dt.$$

2.3 Fading Rate

For a particular receiver sensitivity the minimal acceptable received power is specified. If the power and gain of the transmitting system, the effective aperture of the receiver antenna, and the trajectory of the ECHO II are given, then by using the radar equation,

$$P_r = \frac{P_t\ G\ A_r}{16\ \pi^2\ R_t^2\ R_r^2}\ \sigma ,$$

this received power requirement can be translated into a minimal acceptable value of σ, σ_m. σ_m, of course, varies, depending on the variables R_t and R_r, the respective distances from the balloon of the transmitter and receiver. For a particular value of σ_m, the fading rate is the probability that $\sigma < \sigma_m$, or equivalently, that $f < \sigma_m / \sigma_o$, which from section 2.1, is

$$\Phi\left(\frac{10 \log \frac{\sigma_m}{\sigma_o} + .115 A^2}{A}\right).$$

The fading rate can be interpreted as the percentage of time that the received power is less than the minimal acceptable value.

If, for example, it is desired to have a fading rate < .01, it is necessary that

$$\Phi\left(\frac{10 \log \frac{\sigma_m}{\sigma_o} + .115 A^2}{A}\right) < .01, \text{ or}$$

$$- 10 \log \frac{\sigma_m}{\sigma_o} > .115 A^2 + 2.4 A$$

If $A = 5$, σ_m must be 15 db below σ_o. When this value is inserted into the radar equation the minimal value of P_t can be determined. If $A = 3$, σ_m need be only 6 db below σ_o. Therefore, going from $A = 5$ to $A = 3$ causes a 9 db reduction in the necessary transmitter power, for a fading rate < .01.

2.4 Signal Modulation by the Balloon

Because the radar data determines the amplitude, but not the phase, of a reflected signal, discussion of balloon modulation has been limited to amplitude modulated signals.

The wave form of an amplitude modulated signal can be represented as

$$1 + s(t)$$

where s(t) is the modulation waveform which is the information carrying signal. If there is no further modulation by the transmission path, the waveform arriving at the receiver is unchanged and the detected waveform will be

$$s(t) + n(t),$$

where n(t) is the noise of the receiver system. This picture changes when the transmission path modulates the signal.

In particular, after reflection by the balloon, the waveform arriving at the receiver is

$$(1 + s(t))\sqrt{\frac{\sigma(t)}{\sigma_o}} = [1 + s(t)]\sqrt{f}.$$

The modulation waveform is therefore

$$s(t)\sqrt{f} + (\sqrt{f} - 1) = s(t) + (1 + s(t))(\sqrt{f} - 1)$$

The detected signal is then

$$s(t) + (1 + s(t))(\sqrt{f} - 1) + n(t).$$

The term $N(t) = (1 + s(t))(\sqrt{f} - 1)$ is noise which has been added to the information carrying signal $s(t)$. <u>If the signal ensemble is specified</u>, s is a random variable. Then $N(t)$ is a random variable whose distribution can be determined on the basis of the following fact:

If F, G are independent random variables with probability densities, respectively $D_F(x)$, $D_G(x)$, then the probability density for the random variable $F\,G$ is

$$D_{FG}(x) = \int_{-\infty}^{\infty} D_F(y)\, D_G\left(\frac{x}{y}\right) dy$$

Thus, since in 2.1 we have determined the distributed function for f and hence for $\sqrt{f} - 1$, it is possible to find the distribution function for N. The average noise power is then the expected value

$$\langle N^2 \rangle = \left\langle (1 + s)^2 (\sqrt{f} - 1)^2 \right\rangle ,$$

and the signal to noise ratio

$$\frac{\langle S^2 \rangle}{\langle N^2 \rangle} ,$$

is the highest possible signal to noise ratio, even if the system noise is zero.

We have computed this ratio for two different signal ensembles:

a. s is uniformly distributed over the range $-P \leq x \leq P$, where $0 \leq P \leq 1$, P representing the modulation percentage. In this case

$$\frac{\langle S^2 \rangle}{\langle N^2 \rangle} = \frac{1}{16\ A^2} \frac{P^2}{1 + P^2} \times 10^4$$

For A = 5, this ratio is approximately 12 for P = 1 and 6 for $P = \frac{1}{2}$.
For A = 3, the value of the ratio is approximately 33 for P = 1 and 16 for $P = \frac{1}{2}$.

b. S = 0 and -1 with equal probability (keyed CW transmission). In this case,

$$\frac{\langle S^2 \rangle}{\langle N^2 \rangle} \sim \frac{3}{2} \frac{10^4}{A^2}$$

Here even for A = 10, the ratio is 150.

2.5 Bistatic Effects

It should be observed that the values of σ obtained during the ECHO II flight tests are monostatic; corresponding to receiver and transmitter being at the same location. On the other hand, for communications purposes, the receiver and transmitter are separated; the appropriate σ is the bistatic cross-section. In earlier work it was determined that for bistatic angles $\leq 30^{\circ}$, and for frequencies > 170 MC, the bistatic cross-section can be obtained from the monostatic cross-section. In the Static Inflation Tests, the radar cross-sections obtained by bistatic measurements were found to correlate with the monostatic radar cross-section computed on the basis of photogrammetric measurements, thus verifying the earlier analysis. For lower frequencies and larger bistatic angles it is estimated that the radar cross-section statistics, obtained by monostatic radar measurements are applicable to bistatic angles of at least 90°, and for frequencies greater than 100 MC.

III. BALLOON GEOMETRY

3.1 Anomalies in the Data

The possible effect of ECHO II balloon deformations from a nominal spherical shape on the radar returns received from the balloon was investigated. This analysis and any resulting computer programs should be suitable for processing not only ECHO II data received from different radar sites but also data from other similar satellites which NASA/GSFC wishes to analyze.

As discussed briefly in Section 1.2.5 there are present in some of the data certain unexpected features. The most important of these is a periodic drop in the radar return which endures for several seconds. The possible dependence of this feature on variations in the wavelength, and the extent of its consistency throughout the data, as well as the questions of whether its true period may be 50 seconds rather than 100 seconds is subject to verification by means of the data processing programs which, at the time of writing, are essentially complete. Upon examination of simultaneous beacon and radar data obtained by RRE, this effect appears to be well correlated with the periodic nature of the beacon data. This simultaneous data is shown in Figure 2 and suggests an interesting hypothesis which will be the subject of discussion in Section 3.1.1 of this report.

In any case the best explanation of this "drop out" effect seems to be to attribute it to the effect of one or more deformed areas on the surface of the balloon which affect the radar return once each rotation. The apparent qualitative difference between the 50 seconds preceding the drop out and the 50 seconds following it could easily arise from a difference in extent or kind of deformation of the two sides of the balloon

As to the sharp rapid oscillations of the return, it has been tentatively suggested that this effect might arise from interference between multiple scattering centers on the balloon. The techniques which can be used to examine this possibility have been described in precise mathematical detail in Reference 4, but a brief resume is given in Section 3.2.3 of this report.

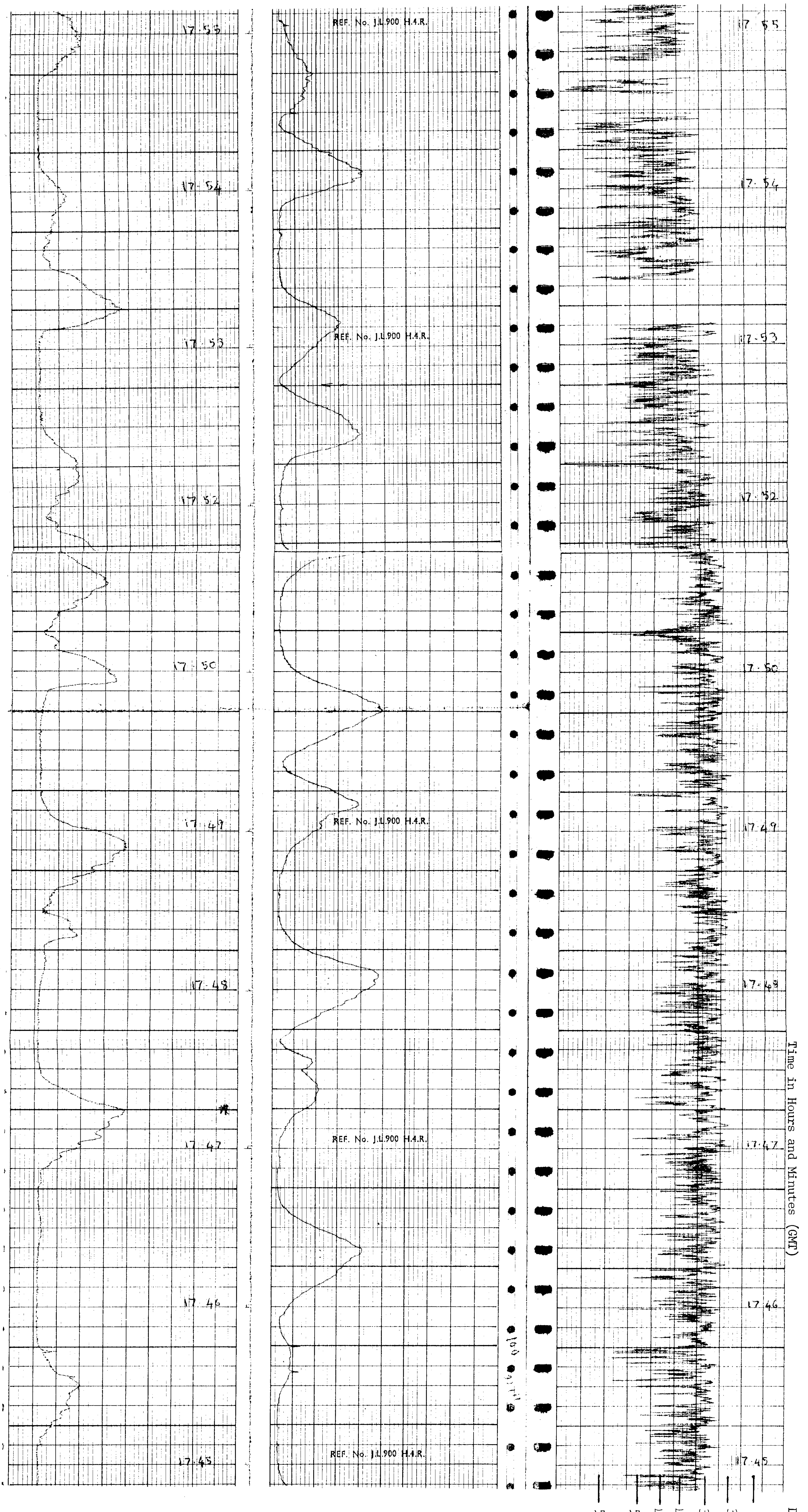


FIGURE 2

SIMULTANEOUS RADAR AND BEACON DATA, 28 January 1964, RRE

3.1.1 Connections Between Anomalies and Deformation of the Balloon

The most plausible explanation of the "drop out" effect is that the balloon rotation causes the portions of the balloon containing the solar panels and telemetry beacons to bulge out into a wedge shape. The cross section of such a shape has been computed and could account for the effect as noted in some of the data.

In what follows several possible mechanisms are examined for their potential effect on the radar cross section return from the balloon. It will be seen that of the various forms a deformation may take, a wedge shape seems best to fit the data. In Section 3.2, the statistical methods used to verify, modify, or reject these hypotheses are discussed.

a. Wedges

By observing the Malvern radar and beacon data, it is noted that on the gores of the balloon corresponding to the location of the "drop out" are mounted solar panels and telemetry beacons. Because the balloon is rotating, this equipment exerts an outward directed force. Suppose that as a result of this force on the balloon, the shape near these gores appears as in Figure 3.

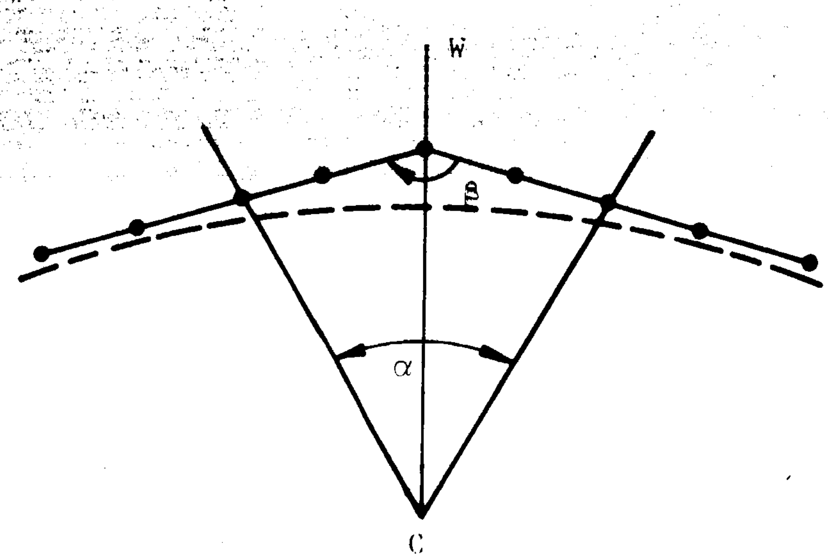


FIGURE 3

In Figure 3, the dotted line indicates the sphere contour, C indicates the center of the balloon, and W represents the seam joining the two reinforced gores on which are mounted the equipment. The resulting cross section, for aspect angles within the angular domain indicated by α would be that of a cylindrical wedge, and considerably lower than that of the nominal balloon cross section. The backscattering cross section of the wedge is approximately

$$\frac{R\lambda_o}{4} \tan^2 \beta/2$$

where λ is the wavelength and β is the wedge angle. Also, the distance $WC = R_o / \cos \frac{\alpha}{2}$. For a 10 db drop out at the Millstone frequency, $\alpha = 10.6^o$, as compared to the actual drop out interval of 18^o. For this value of α, WC = 67.8 ft., requiring the radius to have been "pulled out" only .3 feet.

Conversely, for $\alpha = 18^o$, the wedge cross section will be approximately 58 m^2, giving a drop out of 13 db. For this value of α, WC = 68.2 ft., requiring the radius to have been "pulled out" .7 feet. Thus this hypothesis is consistent with the Millstone data observed. The hypothesis is subject to further test by comparing the result with data at other frequencies in the data reduction program.

b. Wrinkles

If it is assumed that the wrinkles are parallel to the gore seams, then a drop in signal from the beacon region could be accounted for by a change in curvature of the surface in this region. Since the wrinkles are assumed to be parallel to the gore seams, the radius of curvature in the direction of the gore seams can be assumed to be that of the balloon, namely 67.5 feet. Assuming this radius of curvature in one direction, in order to obtain a signal drop of 10 db, the other radius of curvature would have to be about 6.75 feet. Actually this 6.75 feet radius would be a mean value since the return signal varies approximately $\pm$ 6 db. Therefore, the equivalent radius of curvature in the depressed region could vary between 1.8 feet and 27 feet and be made up of many wrinkles that can present a signature with an equivalent radius range. Also, since the drop in signal strength occurs for several seconds, more than one gore would probably be presented in this period (assuming a period of 100 seconds), thereby indicating more than one wrinkle. The drop in signal does not remain around 10 db over the complete pass which might indicate that the effects are not constant over all aspects. This could add support to the wrinkle theory since the wrinkles would not be as prevalent away from the equator of the balloon as at the equator if the wrinkles are oriented parallel to the gore seams.

c. Folds

A fold is defined as an overlapping region on the balloon having a curved portion at each crease and flat portions between the creases. A fold tends to be frequency sensitive whereas a wrinkle tends to be non-frequency sensitive. The analysis of folds is similar to that of the wrinkles. A single fold would exhibit polarization sensitivity.

d. Flat Spots

Flat spots could occur in the reinforced gore region since the addition of the beacon and associated solar cells might tend to strengthen this region and reduce the possibility of the balloon forming a curved surface. However, it seems more reasonable that this region does not form a flat plate but instead a cylindrical shape in which the radius of the balloon along the gore seam remains about the same as that of the inflated balloon, and the surface perpendicular to the gore tends to flatten especially around the beacon area. This might be substantiated in that the radar signature of the balloon as observed from Millstone did not appear to be very aspect sensitive and assumed cylindrical scattering from the balloon near the equator region would also not be sensitive as one moved from the upper hemisphere to the lower hemisphere.

e. Holes

The radar cross section of the hole in a sphere when the wavelength is small with respect to all diameters can be computed by evaluating the hole rim contributions by a modification of the Sommerfeld semi-infinite plane solution and then evaluating the geometric optics contribution of the inner surface of the sphere. For a large hole, at backscattering, these two terms are of the same order of magnitude and by proper arrangement of phase can combine to give a deep null. For the ECHO II balloon, which is not quite a perfect sphere, the above remarks can serve as a rough model. However, it requires a very fortuitous arrangement of geometric parameters and frequencies to provide a backscattering null, throughout the balloon history, since drop-outs of varying widths have been observed from all radar sites. On this basis alone, the hole theory appears unacceptable. Even more conclusive is the angular spread of the drop out. The cross section of a hole has a lobe structure of an equivalent radiating aperture, the major lobe having the beam width $\sim \lambda/d$, where λ is the wavelength and d the aperture diameter. At radar frequencies it would require an extremely small diameter to account for the angular width of the drop out (time intervals up to 6 seconds), and in this case the hole would make an extremely small contribution to the cross section. On this basis, the hole theory appears to be ruled out.

3.2 Statistical Methods of Examination of Balloon Geometry

As has been indicated in preceding sections of this report, the ECHO II radar data available thus far has been in the form of analog recordings. Though these recordings form a basis for quick analysis of the results, the information they contain is of a nature that restricts one to qualitative judgment.

The first requirement to begin the data reduction and analysis was preparation of a reformatting program which would extract from the data tapes the received power calibration, range, and making the necessary conversion to radar cross section information, put the output into a uniform format. This program is complete and is documented in Reference 5. Simultaneously, the first of several statistical programs (discussed in Section 3.2.2) was formulated and is now in the final stages of program checkout. Further computer programs are in the formulation process and are described below.

3.2.1 Precise Determination of Anomalies

With the help of the computer program whose formulation is briefly described in Section 3.2.2 it will be possible to determine much more precisely the characteristics of the anomalies in the radar return which have been discussed above. In particular, the extent and intensity of the drop-outs will be subject to analysis to determine whether or not they vary as functions either of time since launch or of wavelength. Since some of the postulated explanations of the connection between anomalies in a radar return and balloon geometry would be frequency sensitive and others would not be this process should make possible more firm conclusions as to possible deformations of the balloon.

A second approach to the question of frequency sensitivity has been considered which will also permit examination of possible dependency of the return upon polarization. This will involve preparing a computer program to analyze radar data as specified by the following quotation from Reference 6.

"Let us consider a perfectly conducting body of arbitrary convex shape on which a plane wave is incident. It will be assumed that the receiver is in the far field of the body regarded as a scatterer.

Since the body is perfectly conducting, the reflection coefficient is unity, and the leading term in the asymptotic expansion of the cross-section for small wavelengths is given by geometrical optics. If the body has no corners or faces perpendicular to Poynting's vector, the geometrical optics cross-section is wavelength independent and is simply

$$\sigma = \pi R_1 R_2, \tag{1}$$

where R_1 and R_2 are the principal radii of curvature of the specular region. For backscattering, the center of the specular region is that point on the body which is nearest to the receiver. In the particular case in which

$R_1 = R_2 = a$, Equation (1) reduces to

$$\sigma = \pi a^2, \tag{2}$$

which will be recognized as the cross section of a perfectly conducting sphere of radius a.

"If the body is not smooth and convex, but is still perfectly conducting, other portions may contribute towards the scattering cross section, and while small scale irregularities will not be considered, any large scale perturbation must be taken into account. Falling into this category is a corner reflector or large flat area, the cross section of which is

$$\sigma = \frac{A}{\lambda^2}, \tag{3}$$

where A is proportional to the square of the area. For positions of the receiver in the direction of peak return, A is essentially wavelength independent.

"A second type of structure is a conelike projection of small included angle and the cross section of this is

$$\sigma = C\lambda^2 \tag{4}$$

where C is independent of the wavelength. If both types of scatterers are present on the body, the total cross section can be written in the form

$$\sigma = \frac{A}{\lambda^2} + B + C\lambda^2 \tag{5}$$

with $A, B, C > 0$. In this expression, B represents the geometrical optics cross section of the unperturbed body."

At the present time simultaneous radar data at several frequencies is available only from Wallops Island but it will probably be sufficient to determine values for the coefficients A, B, and C from which one can determine whether A and C are statistically significant quantities. The coefficient B corresponds to the geometric optics cross section of a sphere and should unquestionably be the dominant term.

3.2.2 Auto-Correlation and Power Spectrum Program

A statistical analysis program with the following capabilities is available:

1. Radar cross section values - in square meters - between T min and T max are considered.
2. This time interval is broken up into a series of sub-intervals, alternating a to-be-considered sub-interval and a to-be-ignored sub-interval. The number of points per sub-interval, for each type of sub-interval, is an input parameter; in some cases the number of points per to-be-ignored sub-interval are zero.
3. The median cross section value for each to-be-considered sub-interval is computed. Let X_i be the value of the i^{th} such sub-interval.
4. There is a sense switch option to compute and display histograms of the X_i.
5. The mean and standard deviation of the set of X_i are computed by the following formulae:

$$\overline{X} = \sum_{i=1}^{n} X_i/n$$

$$\sigma^2 = \left(\sum_{i=1}^{n} X_i^2\right)\left(\frac{1}{n}\right) - \overline{X}^2$$

where n is the number of sub-intervals to-be-considered.

6. It is possible to compute a set of auto-correlations, ρ_i, i = 1,...,m, by either equation (6) or equation (7):

$$\rho_i = \frac{\sum_{j=1}^{n-i}\left(X_j - \overline{X}\right)\left(X_{j+i} - \overline{X}\right)}{(n-i)\ \sigma^2} \qquad (6)$$

$$p_i = \frac{\sum_{j=1}^{n-i} X_j X_{i+j} - \left(\frac{1}{n-i}\right)\left(\sum_{j=1}^{n-i} X_j\right)\left(\sum_{j=1}^{n-i} X_{i+j}\right)}{\left[\sum_{j=1}^{n-i} X_j^2 - \frac{1}{n-1}\left(\sum_{j=1}^{n-i} X_j\right)^2\right]^{\frac{1}{2}}\left[\sum_{j=1}^{n-i} X_{j+i}^2 - \frac{1}{n-1}\left(\sum_{j=1}^{n-i} X_{j+i}\right)^2\right]^{\frac{1}{2}}} \qquad (7)$$

7. It is obvious that equation (6) is much more convenient computationally then (7); and, for most cases, (6) is a satisfactory approximation to (7). There is a provision to display the ρ_i.

8. The program is able to compute power spectra, P_h, $h=1,\ldots,m$, by the following formula, using either set of ρ_i.

$$P_h = \frac{2\Delta\tau}{\pi} \sum_{k=0}^{m} \epsilon_k \rho_k \cos\frac{h k \pi}{m} ,$$

where:

$$_o = 1,$$

$$\epsilon_k = 1 \text{ for } 0 < k < m,$$

$$\epsilon_k = \tfrac{1}{2} \text{ for } k = 0,\ m,$$

$\Delta\tau$ = the interval in seconds between the start of successive to-be-considered intervals.

9. The program is able to display these power spectra.

3.2.3 Statistics of Multiple Scattering

A preliminary analysis has been performed which indicates that the radar cross section return in db will be normally distributed about the mean radar cross section in db. This work has been reported in Reference 4 but will be briefly reviewed here. One of the computer programs being prepared will test the hypothesis that the digital radar data is log normally distributed. Two conjectures have been advanced which can explain this distribution of the radar return. The first of these is based on the fact that the balloon is not truly spherical but instead has a shape for which the two principal radii of curvature vary about the expected radii of curvature as a function of aspect angle. If this is so, the radar cross section would vary with aspect angle and for a given aspect angle would have the form

$$\sigma = \pi R_1 R_2.$$

If we now assume that the difference between log R_1 and its average value and the difference between log R_2 and its average value are normally distributed, then the radar cross section in db will also be normally distributed about its mean value in db. Several graphs have been prepared which illustrate distribution parameters of log R_1 and log R_2 which could yield the observed distribution parameters of log σ. Work is now taking place on whether this assumption is a reasonable one.

A conjecture which may prove to be useful here is that examination of the photogrammetric maps produced during the static tests will yield log normally distributed radii of curvature. This point will be the subject of further investigation. Its significance is that it would provide a means of estimating the local deviations of the balloon from spherical.

Another explanation which has been advanced to account for the apparent log normal distribution of the cross section return is the possibility of the presence of two independent scatterers whose returns combine in a fashion which produces a normal return. If two cross sections which are essentially constant combine with random relative phase, then the return has a distribution whose closeness to a normal distribution depends on the relative magnitude of the two scattering bodies. Such combination in random fashion might be caused by random changes in the relative location of a fixed pair of scattering centers. Further examination is now being made of the possibility that the phase angle could be uniformly distributed, i.e., that any phase angle is equally likely.

IV. CONCLUSIONS

The radar portion of the flight test experiment monitored the cross section of ECHO II as a function of time. As a result of physical inspection of the analog data and of preliminary processing of the digital data, it is possible to offer at this time preliminary conclusions concerning the physical description of the balloon and its quality as a passive communication satellite.

4.1 Physical Description of ECHO II

Subject to further validation through data processing the following conclusions are advanced:

a. The balloon inflated to a generally spherical shape having approximately the design radius of 67.5 feet.

b. The sphere has many minor perturbations in its shape and at least one major deformation, as indicated by the marked drop in cross section shown in Figure 2.

4.2 Effectiveness as a Communication Satellite

With the data obtained and the radar cross section statistics derivable from this data, it is possible to estimate the effectiveness of ECHO II as a communications satellite as is shown in Section II. For typical systems parameters relative to high quality audio transmission (20 kc band width), at a carrier frequency of 5000 mc a fading rate of 0.05 percent is predicted. For lower frequencies the quality deteriorates. The ECHO II is predicted to be a reliable communications satellite for frequency modulated signals at frequencies greater than 2000 mc.

4.3 Anomalies

Anomalies exhibited in the radar cross section data can be explained in terms of minor geometric perturbations of the balloon surface. Other explanations which have been offered, in particular:

a. plasma effects

b. holes in the balloon

c. multi-pathing

have been examined in quantitative detail and are inconsistent with either the data or with well established physical laws.

4.4 Short Duration, Large Amplitude Scintillations

The flight data exhibits one effect which is difficult to explain on the basis of ground test results. This is the existence in the time dependent radar cross section patterns of short duration scintillations of up to 20 or 25 db. Because of their short duration (often of the same order as that of typical recording pen recovery speeds, i.e., about 1/8 second) these scintillations have little effect on the radar cross section statistics.

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6. T. B. A. Senior, K. M. Siegel, "A Theory of Radar Scattering by the Moon", Journal of Research, Vol. 64D, No. 3, May-June 1960.